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Development of Streamwise Counter-Rotating Vortices in Flat Plate Boundary Layer Pre-set by Leading Edge Patterns

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Abstract: Development of streamwise counter-rotating vortices induced by leading edge patterns with different pattern shape is investigated using hot-wire anemometry in the boundary layer of a flat plate. A triangular, sinusoidal and notched patterns with the same pattern wavelength λ of 15mm and the same pattern amplitude A of 7.5mm were examined for free-stream velocity of 3m/s. The results show a good agreement with earlier studies. The inflection point on the velocity profile downstream of the trough of the patterns at the beginning of the vortex formation indicates that the vortices non-linearly propagate downstream. An additional vortex structure was also observed between the troughs of the notched pattern.

Keywords: Leading edge pattern, Streamwise counter-rotating vortices, Flat plate boundary layer, Hot-Wire Anemometry.

1. Introduction

Development of streamwise counter-rotating vortices within the boundary layer is a well-known passive flow control resulting in the momentum exchange between the free-stream flow and the boundary layer flow. Such vortices cause the boundary layer to be re-energized and the transition process to be expedited. The streamwise counter-rotating vortices,

generated in either natural or forced manner, can be observed in many engineering applications such as airfoils, turbomachines and heat exchangers. Such streamwise counter-rotating vortices are generally developed as secondary flow in instability problems. Rayleigh (Rayleigh 1920), Taylor-Couette (Taylor 1923), Dean (Dean 1928), Görtler (Görtler 1941) instabilities are the well-known examples demonstrating the existence of such streamwise counter-rotating vortices. The wavelengths of the natural counter-rotating vortices are often variable as a result of a competition of perturbation with different amplification rates ((Mitsudharmadi et al., 2004 and Winoto et al. 2005). To examine the vortices in a controlled environment, perturbation devices such as a vortex generator (Lin 2002), thin wire (Peerhossaini & Bahri 1998 and Mitsudharmadi et al., 2004) and roughness (Denier et al. 1991) were used to induced its formation. The leading edge pattern is another approach to pre-set streamwise counter-rotating vortices (Nishilawa et al. 2007; Hasheminejad et al. 2014; Hasheminejad et al. 2016). It is inspired by the observations of humpback whales which are more agile in pursuing their prey compared to the other whales.

The preliminary investigation revealed that the leading edge protrusions of humpback whales flippers are the distinctive feature of this species (Fish & Battle 1995; Fish et al. 2011). The leading edge protrusions cause earlier flow separation downstream of the valley between the adjacent protrusions which bring about changes in aerodynamic characteristics of an airfoil (Johari et al. 2007). This approach can also increase stall angle or prevent dramatic lift drop at post-stall and raise the maximum lift (Miklosovic et al. 2004). However, there is no benefit on the pre-stall condition due to the leading edge protrusions (Stein & Murray 2005; Johari et al. 2007; Miklosovic et al. 2007; Hansen et al. 2011).

The leading edge protrusions are functionally comparable to conventional vortex generators and delta-wings due to the similarity in the development and characteristics of such streamwise counter-rotating vortices within the boundary layer (Hansen et al. 2011; Wei

et al. 2015). The geometrical features of the leading edge protrusion including the amplitude and wavelength affect the aerodynamic performance of the approach due to changing the vortex structures (Johari et al. 2007; Cranston et al. 2012; Hansen et al. 2011). The surface curvature, configuration of the bumpy surface and Reynolds number are the other parameters that affect the effectiveness of the leading edge protrusions (Cranston et al. 2012; Hansen et al. 2011; Budiman et al. 2014).

To have a more insight on the role of leading edge pattern to the evolution of streamwise counter-rotating vortices, the flat plate model with the leading edge pattern were used in the current study. In the previous study of the Görtler instability, the initial occurrence of streamwise counter-rotating vortices is indicated by the waviness of the boundary layer thickness along the spanwise direction (Winoto & Crane 1980; Winoto & Low 1991; Mitsudharmadi et al., 2004, 2005a, 2005b, 2006; Tandiono et al. 2008; Tandiono et al. 2013). As it evolves downstream, the perturbation is amplified and the waviness shape will transform into the mushroom-like structures. It causes the low momentum fluid to be lifted up from the wall in the “upwash region” where the boundary layer is thicker. The upward movement of the low momentum fluid is indicated by the formation of the stem of the mushroom-like structures. Since this low momentum fluid cannot penetrate the high momentum in the free-stream, it will be deflected down to form the mushroom hat. This causes the entrainment of high momentum fluid from the free-stream into the boundary layer in the downwash region where the boundary layer is thinner. Due to this, the velocity profile in the downwash region is fuller than that in the upwash region.

Unlike the occurrence of the streamwise counter-rotating vortices in the Görtler instability study, it has been reported that the presence of leading edge patterns, regardless the geometrical shape of the pattern, generate streamwise counter-rotating vortices which evolve to form the mushroom-like structures in the boundary layer flow past a flat plate immediately

downstream of each trough of the leading edge pattern (Hasheminejad et al. 2014; Budiman et al. 2014; Hasheminejad et al. 2016; Budiman et al. 2016). The vortices are diffused quickly and eventually break down into turbulence further downstream due to disturbance amplification and mixing enhancement.

The objective of the present work is to quantitatively examine the development of streamwise counter-rotating vortices in a flat plate boundary layer downstream of three different leading edge patterns by means of hot-wire anemometry. The leading edge patterns are triangular, sinusoidal and notched patterns with the same geometrical wavelength and amplitude.

2. Experimental details

The experiments were conducted inside an open-loop, low-speed wind tunnel connected to an Acrylic rectangular test section with a cross-section of 150 mm×600 mm extended to 235cm. The wind tunnel is equipped by a honeycomb composed of five rectangular mesh screens, a two-dimensional contraction chamber with contraction ratio of 4:1 to keep the flow turbulence intensity of less than 0.45% for the free-stream velocity (U_∞) range of 1.0 to 4.0 m/s (Fig. 1a). A 3mm thick flat plate with a specific leading edge pattern is fixed inside the test section while the distance from the bottom and the top walls of the channel are 50mm and 100mm, respectively. The leading edge of the plate is tapered with an acute angle of 20° to avoid the separation bubble. Each leading edge pattern consists of eight cycles characterized by the wavelength (λ) of 15 mm and amplitude (A) of 7.5mm (Fig. 1b). In the case of the notched leading edge, each notch is 1mm wide. Table 1 summarizes the dimensions and the adopted terminology of the leading edge patterns used in this work. The experiments were conducted at the free- stream velocity of 3m/s for all the patterns. A Cartesian coordinates system is defined to represent the streamwise (x), wall-normal (y) and

spanwise (z) directions from the middle of the leading edge which is indeed the middle peak of the pattern.

Table 1 Pattern configurations and adopted terminologies

Type of pattern	Configuration		A/ λ ratio	Label
Triangular pattern	$\lambda = 15\text{mm}$	$A = 7.5\text{mm}$	0.5	T- $\lambda 15A7.5$
Sinusoidal pattern	$\lambda = 15\text{mm}$	$A = 7.5\text{mm}$	0.5	S- $\lambda 15A7.5$
Notched pattern	$\lambda = 15\text{mm}$	$A = 7.5\text{mm}$	0.5	N- $\lambda 15A7.5$

Fig 1. Schematic of (a) experimental Set-up (b) leading edge patterns (left to right): triangular (T- $\lambda 15A7.5$), sinusoidal (S- $\lambda 15A7.5$) and notched patterns (N- $\lambda 15A7.5$)

A boundary layer hot-wire probe (DANTEC 55P15) connected to a Constant Temperature Anemometer (CTA) is used to measure the streamwise mean velocity and its fluctuations components. The probe is mounted on a traversing mechanism controlled by two step motors to move the probe in the spanwise (z) and wall-normal (y) directions with a precision of ± 0.01 mm. The measurements are taken at several streamwise locations and in the y-z planes for the range of $-1 \leq z / \lambda \leq +1$ ($-15 \text{ mm} \leq z \leq +15 \text{ mm}$), covering a spanwise distance of two middle troughs of each pattern, with a step size of 1.0 mm in the spanwise (z) direction and 0.1 to 1 mm in the wall-normal (y) direction.

The output signal of the CTA is low-pass filtered by an analog filter at 3 kHz and sampled at 6 kHz for 21 seconds. A Pitot-static tube linked to a pressure transducer is placed above the hot-wire probe and at the center of the test section for conducting in-situ calibration of the hot-wire before the start of the experiment and to monitor the free stream velocity during the experiment. The calibration is checked during the experiment at the beginning and the end of the experiment to ensure that the uncertainty of the measured data is less than 2%, otherwise, the collected data are rejected and the acquisition process is repeated.

3. Results and Discussion

The flow field velocity data collected by the hot-wire anemometer were post-processed using TECPLOT software to generate the velocity and the turbulence intensity contours. The measurements were done at the same streamwise locations for all the leading edge patterns to compare the effect of the leading edge shape on the flow-field characteristics.

3.1. Mean Velocity

The mean streamwise velocity contours were plotted by normalizing the local streamwise velocity u with the free-stream velocity U_∞ . The contours of this normalized mean

streamwise velocity (u/U_∞) at several streamwise locations downstream of the triangular leading edge are shown in Figs. 2 (a)-(d). As evidence in Fig. 2a, the wavy contours at $x = 10\text{mm}$ indicate emerging counter-rotating vortices immediately downstream of the leading edge pattern trough, that is, in agreement with the earlier works (Hasheminejad et al. 2014; Hasheminejad et al. 2016). In contrast with the appearance of pre-set Görtler vortices which show the initial development of the streamwise counter-rotating vortices in the form of the wavy shape which evolves into the mushroom-like structures, the contours shown in Fig. 2a do not show the formation of the wavy shape. Instead, it shows the appearance of the mushroom-like structures immediately downstream of the leading edge pattern trough at $x = 10\text{mm}$. The height of the vortices at $x = 10\text{ mm}$ is about three times as high as the corresponding Blasius boundary layer. It shows that the perturbation has been rapidly amplified due to the presence of the leading edge pattern. As a result, the formation of the mushroom-like structures becomes very prominent at $x = 20\text{mm}$ (Fig. 2b) and it starts diffusing at x about 30mm (Fig. 2c.).

During the vortex growth, the high-shear region near the boundary layer and the inflection point move away from the wall. Accordingly, the mushroom-like structure becomes weak and susceptible to free-stream flow. They eventually become diffused from $x = 30\text{mm}$ and break down into turbulence due to the increase in mixing (Fig. 2(d)). It is also shown in Fig. 2 that each trough of the triangular leading edge pattern creates a symmetric counter-rotating vortex.

As shown in Figs. 2, the low momentum fluid at the trough moves upward and results in the appearance of a low-speed region indicated by thick boundary layer known as upwash. On the other hand, downwash region takes place downstream of the pattern peaks which contains high momentum deflected toward the wall. The downwash region is identified by the thinner boundary layer as a consequence of the boundary layer thickening at upwash. The

thicker boundary layer at upwash is more vulnerable to inflectional point and ultimately instability. It is understood that the vortices produce inflexions in the streamwise velocity profiles. Only vortices of sufficient strength are unstable and produce turbulent flow (Yang 1987).

Fig. 2. Contours of normalized mean streamwise velocity (u/U_∞) on y-z plane for triangular pattern T - $\lambda 15A7.5$

The upwash region are the spaces between the peaks of the pattern that is exactly similar to that reported for airfoils with leading edge protuberances (Hansen et al. 2011; Rostamzadeh et al. 2013; Rostamzadeh et al. 2014; Wei et al. 2015). Such flow structure is also observed when a number of spanwise roughness is placed on a flat plate. For example, a series of counter-rotating vortex generators cause an upwash region between the neighboring vortex generators (Godard & Stanislas 2006). A roughness array fixed upstream of a flat plate also makes an upwash flow containing low momentum fluid between the roughness elements (Bakchinov et al. 1995).

As reported, the spanwise modulation of the streamwise velocity increases as a result of the downwash move at the edge of the elements and an upwash move in the region between them. However, the spanwise flow ascending from the swept variation in the leading edge pattern produces a vortex rotating toward the peak in the vicinity and move along the swept edge to the trough (Wei et al. 2015). At the space between the peaks, two vortices developed from the corresponding peak converged to create a counter-rotating vortex pair. As the leading edge variation between the adjacent peaks is symmetric with respect to the trough-plane, the counter-rotating vortex pair propagates downstream in streamwise direction with a symmetric shape.

Similar to the triangular pattern, the counter-rotating vortices appear downstream of the troughs of the sinusoidal pattern but slightly smaller (Figs. 3 (a)-(d)). The lower height and narrower width may result from the narrower upwash region due the curvy variation of the leading edge. The diffusion of the mushroom-like structure starts at $x = 30\text{mm}$ like the triangular pattern. Unlike the triangular and sinusoidal patterns, as shown in Figs. 4 (a)-(d), the notched pattern affects the boundary layer resulting in the appearance of two type of vortices: one streamwise vortex structure downstream of the troughs and another additional

vortex structure downstream of the peaks. The appearance of such extra vortices is also observed in a smoke-wire flow visualization by Hasheminejad et al. (2014). The additional vortex structure downstream of the peaks is smaller than the main vortices and diffuses earlier. The turn-over zone of the main vortices might cause the additional upwash region. The appearance of the additional vortices results in the appearance of more upwash region than those in the other two cases of leading edge pattern. It makes the boundary layer more susceptible to instability that will lead to the breakdown of the mushroom-like structures prior to turbulence.

The appearance of mushroom-like structure, is attributed to the non-linear instability in which an inflection point appears in the velocity profile at the upwash region. The inflection point indicates a high shear layer near the edge of the boundary layer (Inagaki & Aihara 1995).

Fig. 3. Contours of normalized mean streamwise velocity (u/U_∞) on y - z plane for sinusoidal pattern S- $\lambda 15A7.5$

Fig. 4. Contours of normalized mean streamwise velocity (u/U_∞) on y - z plane for notched pattern N- $\lambda 15A7.5$

The non-dimensional velocity profile (u/U_∞) against non-dimensional coordinate normal to the wall $\eta = y\sqrt{U_\infty/x\nu}$ is plotted in Figs. 5(a)-(h) for downstream of the trough (Figs. 5(a)-(d)) and peak (Figs. 5(e)-(g)) of the patterns for different streamwise locations. The profiles with inflection points indicate the presence of an upwash region.

As presented in Figs. 5(a) – (d) the inflection point are evidenced in the velocity profiles downstream of all leading edge patterns. The inflection points observed in $x = 10\text{mm}$ which coincides with the appearance of mushroom-like structures indicate that the non-linear growth of streamwise counter-rotating vortices occurs immediately downstream of the trough of the leading edge pattern. It is also shown that the velocity gradient for these three cases are much smaller than that of Blasius profile. This velocity gradient is moderated further downstream so that the inflection point start to disappear at $x = 40\text{mm}$. The inflection points associated with the sinusoidal leading edge occur at shorter wall-normal distance compared with the triangular and notched patterns. It could indicate that the growth of the disturbance induced by sinusoidal leading edge pattern is less amplified than those of other two leading edge pattern. As a result, the height of the mushroom-like structures due to the sinusoidal leading edge pattern is shorter than those of triangular and notch leading edge patterns as shown in Figs. 3(a) - (d).

Velocity profiles in Figs 5(e)-(h) reveal that there is no inflection point found in the velocity profiles at downwash region for the triangle and sinusoidal leading edge patterns. It is also shown that the velocity profiles at downwash region are “fuller” than those downstream of the trough which can be attributed to the entrainment of the high momentum fluid resulted from the vortical motion of the vortices. As can be seen in Figs 5 (e)-(g), the streamwise velocity around and between vortices exceeds the free-stream velocity up to 20% for locations near the leading edge ($x = 10\text{-}30\text{mm}$). It implies that the entrainment of the high

momentum fluid has energized the flow in the downwash region. Thus, the flow is more attach to the surface as demonstrated by fuller velocity profiles. Unlike the sinusoidal and triangular leading edge pattern, the velocity profile downstream of the peak of the notched pattern has an inflection point at $x = 10\text{mm}$ and $x = 20\text{mm}$ (Figs. 5 (e) and (f)). This confirms the appearance of the additional vortex structure for the notched pattern compared to the other patterns. The additional vortex structure does not last as long as the vortex structure generated by the notch on the leading edge. It starts to be diffused before $x = 30\text{mm}$ where the inflection point does not exist anymore (Fig. 5 (g)).

Fig. 5. Mean velocity profiles across the boundary layer, downstream of the trough (left) and peak (right) of patterns at several streamwise locations at $U_\infty = 3\text{ m/s}$.

3.2. Turbulence Intensity

To investigate the effect of the streamwise counter-rotating generated by the leading edge patterns on velocity fluctuation growth, the turbulence intensity is calculated at measurement points by the following equation:

$$Tu = \frac{1}{U_\infty} \sqrt{\frac{\sum_{i=1}^n (\hat{U}_i - U_\infty)^2}{n}} \quad (1)$$

where n is the total number of data samples at a given point over the sampling duration, $\hat{U}_i$ is the value of the measured sample and U_∞ is the freestream velocity.

Fig. 6 depicts turbulence intensity profiles downstream of the trough and peak of the patterns for a few streamwise locations. There are two peaks on the profiles associated with the locations close to the leading edge of all the leading edge patterns (Figs. 6(a) and (d)). The second peak is seen at $\eta=10, 8$ and 15 for the location $x = 10\text{mm}$ from triangular, sinusoidal and notched leading edge patterns, respectively. The appearance of such peaks is attributed to the formation of the high shear layer near the boundary layer edge (Inagaki & Aihara 1995; Mitsudharmadi et al. 2004). The intensity and the height of the second peak initially increase at $x = 20\text{mm}$ and then become diffused and eventually vanished as the vortices move farther

downstream. As shown in Fig. 6(d) the turbulence near the wall becomes dominant after the decay of the second peak.

Except for the notched pattern, one peak is observed that is associated with the turbulence near the wall in the downwash region for the triangular and sinusoidal leading edge patterns (Figs. 6 (e)-(h)). It implies that there is no high shear layer formed in this region and thus the boundary layer is stable due to the much thinner boundary layer thickness. In the case of the notched pattern, there are still two peaks on turbulence intensity profiles at $x = 10\text{mm}$ and $x = 20\text{mm}$. This indicates that the notched pattern, unlike the other patterns, is more susceptible to have unstable boundary layer due to a high shear layer which is seen in the entire span. As the upwash region is more susceptible to an instability, thus, the transition may take place earlier compared to the other patterns.

Fig. 6. Distribution of turbulence intensity across the boundary layer , downstream of the trough (left) and peak (right) of patterns at several streamwise locations at $U_\infty = 3$ m/s.

Plotting the u'_{rms} normalized by the free-stream velocity results in turbulence intensity contours as shown in Figs. 7. It is evident in Figs 7 (a)-(c) that the high turbulence intensity surrounds the low-speed streak in the upwash region at $x = 10$ mm resulted from the high shear layer. The appearance of the high turbulence intensity around the low-velocity streaks suggests an association of the developing fluctuations with the upwash region. The strip of high turbulence intensity is broadened across the boundary layer and is simultaneously intensified at $x = 20$ mm. This behavior is halted as a result of the vortex breakdown after $x = 30$ mm and it is then spread out in the boundary layer along with the decay process of the vortices. As shown in Fig. 7, the fluctuations spread-out in the boundary layer causes a layer of high turbulence intensity near the wall along the span, even in the downwash region at locations farther downstream. It has a considerably high amplitude in streamwise vortices though its small scale (Swearingen & Blackwelder 1987). In the case of the notched leading

edge pattern, there is an additional high shear layer to the wall downstream of the peaks of the pattern. Since the developing fluctuations forming the high shear layer are attributed to the presence of the upwash region, the additional layer confirms the appearance of another upwash region which is not as strong as the main one.

It can be concluded that the high turbulence intensity region is divided into two parts: one moving away and the other one approaches the wall. The top one is diffused further downstream as a consequence of the vortex structure breakdown. While the bottom part remains near the wall but extends along the span such that a layer of relatively high turbulence intensity is formed. This phenomenon confirms the appearance of the first peak of the turbulence intensity shown in turbulence intensity profiles (Fig. 6). It can be inferred from the results that the turbulence intensity for the case of the notched leading edge is diffused earlier than those of the other patterns which could be attributed to the more rigorous mixing.

Fig. 7. Turbulent intensity (Tu%) contours on y-z plane for (left to right) (a) T- $\lambda 15A7.5$ (b) S- $\lambda 15A7.5$ (c) N- $\lambda 15A7.5$

3.3.Iso-Shear Contour

Shears along the spanwise ($\partial u / \partial z$) and across the boundary layer ($\partial u / \partial y$) are plotted in Figs. 8 and 9 respectively, based on the mean velocity data. As shown in Fig. 8 (a)-(c), there is a concentration zone of spanwise shear ($\partial u / \partial z$) surrounding the low-speed streaks at the upwash regions due to the appearance of mushroom-like vortices for all leading edge patterns. For the notched pattern, there is an additional comparatively small concentration zone which indicates the appearance of low-speed streak as discussed earlier. It can also be seen that the velocity gradient alternately varies from negative to positive value along the span. It exhibits the appearance of inflectional points in the streamwise velocity profiles along the spanwise direction.

Fig. 8. Iso-shear contours ($\partial u / \partial z$) contours on y - z plane for (left to right) (a) T- $\lambda 15A7.5$ (b) S- $\lambda 15A7.5$ (c) N- $\lambda 15A7.5$

Fig. 9. Iso-shear contours ($\partial u/\partial y$) contours on y-z plane for (left to right) (a) T- $\lambda 15A7.5$ (b) S- $\lambda 15A7.5$ (c) N- $\lambda 15A7.5$

This inflection of velocity profiles occurs due to the low-speed streaks in the streamwise direction (Mitsudharmadi et al. 2004; Winoto et al. 2005). The concentrated spanwise shear ($\partial u/\partial z$) is diffused as the vortices are propagated further downstream associated to vortex structure breakdown due to the enhanced mixing prior to turbulence. Comparison of Figs. 8(a)-(c) reveals that the spanwise shear of the triangular and sinusoidal patterns last longer compared to the notched pattern that the vortices become basically disorganized at $x=80\text{mm}$. Fig. 9 shows the contour of the wall-normal shear ($\partial u/\partial y$) at different streamwise locations. As shown in Figs. 9 (a)-(c), the development of the mushroom-like structures is accompanied

by the appearance of negative values at $x = 10\text{mm}$ and 20mm . The wall-normal distribution of streamwise velocity becomes inflectional below the mushroom hat (turn-over region). The strongest positive wall-normal shear is detected near the wall at downwash region where the boundary layer is thinner. It is in fact the high speed region located downstream of the pattern peak of the triangular and sinusoidal patterns and the space between the main and the additional vortices in the case of the notched pattern. In streamwise direction, the structure of the negative shear is diffused and then the mushroom-like structure becomes disorganized along with the decay process due to the increased mixing.

The instability of the streamwise counter-rotating vortex structure appears in either sinuous or varicose mode. The sinuous mode manifests itself as an unsteady meandering of the basic vortices and associated with the inflectional profiles, which produce the temporal velocity fluctuations near the hat of the mushroom-like vortex structure. As suggested by Girgis and Liu (2006) in the comparison of their computational study to the experimental study carried out by Mitsudharmadi et.al (2004), uncontrolled varicose mode which has fluctuations present on the axis near the wall may also be participating in the contours of turbulent intensity. Therefore, two intense region of fluctuations would be evidenced in the turbulent intensity profiles; one is near wall while the other is near the edge of the boundary layer that is around the hat of mushroom-like structures. The appearance of these two regions can also be distinguished clearly by plotting the contours of spanwise shear ($\partial u / \partial z$) in Fig. 8. The region around the hat of the mushroom-like structures decays as the flow reaches the location where the mushroom-like structures collapse due to the onset of turbulence (Mitsudharmadi et al., 2006). This unstable inflectional spanwise profile is a consequence of the appearance of sinuous mode (Swearingen & Blackwelder 1987; Bakchinov et al. 1995; Andersson et al. 2001; Skote et al. 2002).

Further investigation on the periodicity of the instability is done by presenting the spectra of u' components at $\frac{z}{\lambda}, \frac{y}{\delta} = 0.75$ and $x = 10\text{mm}$ (Fig. 10). This location is selected since the appearance of secondary mushroom is observed in the velocity contours due to the notched pattern while for the other two pattern there is no appearance of any spanwise structures. As presented in the plot of turbulent intensity profiles (Fig. 6e) there are two peaks in the turbulent intensity profiles of the notched pattern while for the other two patterns there is only one peak shown. The Fast Fourier Transform (FFT) process to the u' components reveals the appearance of two distinguished peaks in the spectra of u' components due to the notched pattern. These are attributed to the presence of two intense regions of fluctuation around the shoulder and around the stem of the “secondary mushroom-like structures” formed downstream of the peak of the notched pattern. Unlike the spectra of the notched pattern, there is only one peak shown in the spectra of u' components due to triangular and sinuous pattern. This explains why the boundary layer due to the notched surface is more susceptible to the instability than the other two cases.

Fig. 10 The spectra of the u' components at $x = 10\text{mm}$ and $y/\delta = 0.75$
(a) T-λ15A7.5 (b) S-λ15A7.5 (c) N-λ15A7.5.

4. Conclusion

The development of streamwise counter- rotating vortices generated by leading edge pattern has been investigated for a flat plate with triangular, sinusoidal and notched patterns with the same geometrical wavelength and amplitude for free-stream velocity of 3m/s. The hot-wire anemometer measurements showed the appearance of streamwise counter-rotating vortices immediately downstream of the pattern trough. These vortices grew in the form of mushroom-like structures and were eventually diffused farther downstream and breakdown to turbulence due to the mixing enhancement. The results show that the low momentum fluid

downstream of a trough moved upward while the high momentum fluid downstream of a peak moved downward. The development of the counter-rotating vortices for the leading edge with triangular and sinusoidal pattern is very similar. However, for the notched pattern leading edge, it was revealed that an additional vortex structure is developed downstream of the peaks. This phenomenon has made the boundary layer more susceptible to instability in the full span compared to the boundary layer of the triangular and sinusoidal leading edge pattern. It also provides a high shear layer extended over the entire span which expedites the transition compared to the other patterns. As the sinuses and varicose instability mode are driven by $(\partial u / \partial z)$ and $(\partial u / \partial y)$, respectively, it can be suggested that the transition process is dominated by the sinuous mode. Further development of the sinuous mode under a non-linear condition will eventually lead to turbulent flow.

Nomenclature

A	Amplitude of leading edge patterns (peak to trough)
n	Total number of data samples at a given point over the sampling duration
Tu	Turbulence intensity level of the flow
u'	Fluctuating velocity component in the streamwise direction
u	Mean velocity
$\hat{U}_i$	Velocity of a measured sample
U_∞	Free-stream velocity
x, y, z	Streamwise, normal, spanwise distance

Greek Symbols

δ	Boundary layer thickness based on Blasius solution
η	Dimensionless coordinate normal to the wall $(= y \sqrt{U_\infty / \nu x})$
λ	Wavelength of leading edge patterns

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- The development of streamwise counter- rotating vortices generated by leading edge pattern has been investigated for a flat plate with triangular, sinusoidal and notched patterns.
- For the leading edge with triangular and sinusoidal pattern, the counter-rotating vortices development is very similar.
- An additional vortex structure appears downstream of the pattern peaks for the notched pattern leading edge. Such vortices make the boundary layer more susceptible to instability in the full span compared to the boundary layer of the triangular and sinusoidal leading edge pattern.